

TOWARD A SECOND GENERATION FUEL EFFICIENT SUPERSONIC CRUISE AIRCRAFT

PERFORMANCE CHARACTERISTICS AND BENEFITS

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SUMMARY

The NASA Supersonic Cruise Aircraft Research (SCAR) program has led to the identification of many technological advances applicable to supersonic cruise aircraft. Studies at Boeing in recent years have focused on the integration of these technological advances into a second generation Supersonic Cruise Airliner. This paper briefly reviews the characteristics of the 1971 U.S. SST. The need for greatly improved fuel efficiency and off-design subsonic characteristics is discussed. Engine-airframe matching studies are presented which show the benefits of a configuration designed for much lower supersonic drag levels (blended wing-fuselage) and how well this airframe matches with the new advanced variable-cycle engines. The benefits of advanced takeoff procedures and systems together with the co-annular noise effect in achieving low noise levels with a small cruise-sized engine are discussed. It is concluded that the SCAR technology advances when carefully integrated through detailed engine-airframe matching studies on a validated baseline airplane lead to a much improved supersonic cruise aircraft, i.e., more range, less fuel consumption, noise flexibility and satisfactory off-design characteristics.

INTRODUCTION

At the time of the cancellation of the U.S. SST program in 1971 increased emphasis on low community noise levels had resulted in a configuration which incorporated a large dry turbojet engine with a retractable noise suppressor. This solution to the noise problem caused problems in other areas. The dry turbojet had low thrust capability at supersonic speeds. Oversizing it to provide adequate supersonic thrust resulted in an even larger engine with increased weight, balance, flutter and drag penalties. Furthermore, subsonic performance, already poor, was further degraded by the necessity to operate at lower power settings. The poor subsonic performance meant that on many desirable routes requiring overland subsonic operation, i.e., Rome to New York, extra fuel and/or reduced payloads were necessary. Finally, this poor subsonic performance also meant that even for all-overwater flights, i.e., San Francisco to Honolulu, the necessity to allow for subsonic operation after engine and/or pressurization failure meant carrying extra fuel reserves or off-loading payload.

The need for increased supersonic cruise thrust and much lower subsonic fuel consumption led to investigation of variable cycle engines as well as ways of lowering the supersonic drag levels of the 1971 configuration. The recent emphasis on fuel efficiency has greatly emphasized the latter need, i.e., to achieve the lowest possible airplane drag levels.

SYMBOLS AND ABBREVIATIONS

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

DHTF-CD	duct-heating turbofan, convergent-divergent nozzle
EPNdB	effective perceived noise measured in decibels
FAR	Federal Air Regulation
$F_{N_{REQ}}$	required thrust
G.E.	General Electric
H	pressure altitude
ILS	instrument landing system
L/D	lift-drag ratio
M	Mach number
MTW	maximum taxi weight
OEW	operational empty weight
OEW-ENG	operational empty weight less propulsion pod weight
P&WA	Pratt & Whitney Aircraft
RF	range factor
SCAR	Supersonic Cruise Aircraft Research
SFC	specific fuel consumption
SL	sea level
S/L	sideline
ST ^D	standard day
t/c	wing thickness to chord ratio
T-D/D	transonic thrust margin
TOGW	takeoff gross weight
TOFL	takeoff field length

V_{app} approach speed
VCE variable cycle engine
VSCE variable stream control engine

ENGINE-AIRFRAME MATCHING STUDIES

The NASA Supersonic Cruise Aircraft Research (SCAR) program has led to many technology improvements in the key areas of: aerodynamics, variable cycle engines, and advanced takeoff systems and procedures. Integrated engine-airframe matching studies have been carried out on the 1971 Validated Baseline U.S. SST to determine the performance characteristics of a new baseline airplane incorporating the SCAR technology improvements and to assess the benefits in terms of a better matched configuration with lower fuel consumption, increased range, better economics and good "off-design" performance.

Objectives and Constraints

The object of the engine-airframe matching studies was to develop a supersonic cruise airliner with low fuel consumption matched to the characteristics of the multicycle engines developed in parallel NASA studies which met the objectives and constraints noted in table 1. Relative to the 1971 Baseline SST, design range has been increased to include non-stop Pacific flights while speed, payload, field length and noise objectives and requirements are essentially unchanged. In the areas of climb and cruise performance the objectives and requirements were selected to be responsive to Airlines concerns with the characteristics of the 1971 airplane powered by a dry turbojet engine.

Ground Rules

The basic mission profile and the fuel reserves for the "all-supersonic" design mission used in the engine-airframe matching studies are shown in figure 1. It is worth noting that even on this "all supersonic" basic mission about 20 to 25% of the total fuel is required for subsonic flight conditions and reserves. This, together with the necessity to revert to subsonic flight in the event of engine and/or pressurization failure, places great emphasis on efficient subsonic flight for any supersonic airliner.

The basic airplane characteristics used in the engine-airframe matching studies are shown in table 2. The size of the airplane (gross weight, wing area and payload) was fixed and range was allowed to vary as the figure of merit as different engine cycles and aerodynamics changes were evaluated. Wing span was also held constant and this meant a fixed value of engine thrust was required to meet the takeoff field length requirement. The reason wing area and/or span changes were not a part of the engine-airframe matching

studies is shown in figure 2. The 1971 Baseline SST's small wing area and relatively high span were carefully selected to achieve the smallest possible wing area consistent with community noise, approach speed and fuel volume constraints. Full span wing leading and trailing edge flaps plus a separate trimming tail surface provide good lift/drag ratios for takeoff and landing operations.

Effect of Supersonic Aerodynamic Improvements

The achievement of low supersonic drag, consistent with good subsonic and low speed performance characteristics, was an important design goal for the Baseline 1971 SST. Supersonic cruise lift-drag ratios of approximately 7.5 were validated. However, the need for much improved fuel efficiency led to re-evaluation of many aspects of the design. Trade studies were conducted to determine where increases in fuel efficiency could be made, i.e., where drag could be lowered even if the weight effect resulted in no range gain since this does result in less fuel consumed. As a result of these trade studies the following changes have been incorporated into the baseline airplane:

- . Modified wing planform with revised t/c distribution
- . Blended wing-body
- . Low-drag engine nacelle installation

Together, these changes have resulted in an improvement of about 20% in supersonic lift-drag ratio. The improvement in subsonic lift-drag ratio is only about 2%. The performance benefits of this large improvement in supersonic drag are shown in figures 3 and 4. Figure 3 shows the improvement in range and climb characteristics for the airplane powered by a variable-cycle engine. At a constant airframe weight, a range (and fuel usage) improvement of about 30% is achieved with an engine 20% smaller while maintaining adequate transonic thrust margins and time-to-climb capability. Not all of the weight effects are fully analyzed at this time but it is expected that not more than 25% of this range and fuel usage benefit will be offset by increased airframe weight. Figure 4 shows the effect on cruise efficiency. As expected, the 20% improvement in supersonic drag improves the supersonic cruise efficiency about 20%. However, the subsonic cruise efficiency was improved only about 3%, and even including the benefits of a 20% smaller engine size, the ratio of subsonic/supersonic cruise efficiency was lowered from 1.08 to 0.95. Since the objective was a ratio of 1.0, further improvement in subsonic cruise efficiency (either L/D or SFC) is desirable. It is worth noting that had the airplane not been powered by a variable-cycle engine, but rather the original dry turbojet which powered the 1971 SST, the ratio of subsonic to supersonic cruise efficiency would be much worse, about 0.68; i.e., the improvements in supersonic cruise efficiency brought about by airframe changes are made feasible by improvements in subsonic cruise efficiency brought about by a variable-cycle engine.

Effect of Engine Cycle Improvements

The variable cycle engine is one of the major technology advances that the SCAR program has brought forth. Both G.E. and P&WA, under separate contracts to NASA, have produced propulsion data for this type of engine. The effect of these engine cycle improvements on airplane performance have been determined, accounting for the important interactions between the airframe and the propulsion system. A goal of these studies was to develop an efficient airframe that would take advantage of the special characteristics of these engines, i.e., greatly improved subsonic fuel consumption characteristics.

General Electric Engines

The range and climb characteristics of two 1985 technology variable-cycle engines, the initial GE21/J11-B5 and a later improved version, the GE21/J11-B5B, are compared to a 1975 technology dry turbojet engine, the GE4/J6H2, in figure 5. The engines are installed on the blended wing-body configuration. The GE21/J11-B5 and -B5B are "low augmentor temperature rise" double bypass VCE's with 10% oversized front fan blocks, which permit high mass flow operation for takeoff and for subsonic cruise airflow matching. The -B5B variant has a lower bypass ratio and increased supersonic airflow compared to the -B5.

The initial -B5 variable cycle engine showed a substantial improvement in range (and fuel usage), about 12% relative to the GE4/J6H2; however, a larger engine size was necessary to meet the transonic climb thrust margin requirements.

The cruise efficiency characteristics of both engines are shown in figure 6. The initial -B5 variable cycle engine showed a much improved subsonic cruise efficiency, about 20%, and a small improvement in supersonic cruise efficiency, about 2%. The ratio of subsonic to supersonic cruise efficiency was improved from about 0.75 to about 0.85. Note that the larger engine size required to meet the transonic thrust margin degraded the subsonic/supersonic cruise efficiency ratio by about 4%.

Based upon this installed evaluation of the GE21/J11-B5 engine and upon their continuing cycle improvement studies, G.E. identified several areas of potential improvement which resulted in the -B5B variant. As shown in figure 5, the -B5B variant results in a large improvement in range (and fuel usage), about 22% relative to the GE4/J6H2 at a smaller engine size for maximum range. As shown in figure 6, the cruise efficiency characteristics of the -B5B variant are such that the ratio of subsonic to supersonic cruise efficiency has been improved from about 0.75 to about 0.86. Note that the smaller engine size of the -B5B offsets the decreased subsonic cruise efficiency due to a lower bypass ratio.

Pratt & Whitney Aircraft Engines

The range and climb characteristics of two 1985-1990 technology variable cycle engines, the VSCE-502B and VCE-112C, are compared to a 1975 technology duct-heating turbofan engine, the DHTF-C/D, in figure 7. The engines are installed on the blended wing-body configuration. The VSCE-502B is a variable-stream-control duct-heating turbofan engine while the VCE-112C is a tandem dry turbojet with a single rear valve. Both new engine concepts show a large range (and fuel usage) improvement, about 18%, relative to the 1975 DHTF-C/D at a smaller engine size for maximum range.

The cruise efficiency characteristics of all three engines are shown in figure 8. The two new variable cycle engines show substantial improvements in both supersonic and subsonic cruise efficiencies, about 16% and 12% respectively. The ratio of subsonic to supersonic cruise efficiency has been only slightly degraded from about 0.98 to about 0.96 and remains very close to the objective value of 1.0.

One important item of an efficient variable-cycle propulsion system is the nozzle. A variable flap ejector nozzle has been designed as a part of the SCAR program. This nozzle concept has the potential for high installed performance, particularly with regard to the boattail drag at subsonic cruise conditions. Reduced fuel consumption of up to 15% during subsonic cruise operations, appear possible compared to the auxiliary inlet ejector nozzle. While initial study results indicate no range benefit on the all-supersonic mission due to increased weight, the incorporation of this type nozzle into the variable cycle engines discussed above could be very desirable to achieve equal subsonic and supersonic cruise efficiencies.

Advanced Takeoff Systems and Procedures, Coannular Noise Effects

In the previous sections we have shown that small, light variable cycle engines can be integrated with a low supersonic drag airframe to produce a large improvement in range and hence in fuel consumption and economics. The question remained could low noise levels (FAR 36) be met with this engine-airframe combination.

Performance emphasis on the blended wing-body configuration was focused on takeoff and climbout at a gross weight of 340,200 kg (750,000 lb) with engines sized for best range, 318 kg/sec (700 lb/sec). Particular attention was given to estimating the jet noise at the FAR 36 sideline and community noise stations (noise sources other than jet noise have not yet been identified and quantified for these variable-cycle engines). Performance calculations and noise predictions were made for both the basic FAR takeoff and climbout procedures and also for a modified takeoff and climbout using advanced systems and procedures to minimize noise (table 3). The basic jet noise prediction utilized the method from reference 1 for maximum noise level. Directivity angle effects are based upon current Boeing test data. The SAE procedure does not predict the observed co-annular noise reduction effect

associated with the variable-cycle inverted jet velocity profile. Co-annular noise reduction increments from SAE prediction levels based upon P&WA, G.E. and Boeing test data to date are about 7 EPNdB at takeoff power setting at the sideline, to 5 EPNdB or EPNdB at the community, depending upon the power setting. Co-annular noise reduction increments from SAE are less at cutback than for sideline since the peak noise angle at cutback occurs near 90° instead of 140° for the sideline case. Each of the variable cycle engines discussed previously would benefit from the co-annular effect.

The effect on sideline and community levels of using advanced takeoff procedures and systems compared to current FAR 35 procedures is shown in figure 9. The crosshatched area shows the reduced noise levels after the co-annular effects have been applied. These data show that using FAR 36 rules and an engine thrust to achieve a takeoff field length of 3660 m (12,000 ft) the SAE prediction methods gives a sideline noise level of 117 EPNdB and a community noise level of 120 EPNdB. Co-annular benefits reduce the levels to 109 and 115 for the sideline and community respectively. Hence the co-annular effect can reduce sideline noise to FAR 36 "traded" noise levels with a small, cruise-sized variable cycle engine. However, the community noise level is much too high. These data also show that by using advanced systems and procedures to minimize community noise the community noise level can be reduced to only 105 EPNdB (including the co-annular benefit). This advanced takeoff and climbout involves:

- . Maximum thrust (within sideline noise constraints) during ground roll, taking advantage of ground shielding
- . Thrust reduction during climb (programmed throttles) to control sideline noise
- . Flap retraction during climb (programmed flaps) for better lift/drag ratio.
- . Acceleration during climb to improve lift-drag ratio
- . Cutback at community to less than 3 engine level flight thrust. If an engine fails at this point, APR automatically increases thrust to level flight power setting.

Note that the takeoff field length has been decreased from 3660 m (12000 ft) to 3200 m (10500 ft) since power has increased during the ground roll to take advantage of ground shielding. An alternate procedure is shown to minimize sideline noise. Here power is reduced during ground roll consistent with a takeoff field length of 3660 m (12000 ft). Sideline noise is reduced 4 EPNdB. This will result in less acceleration to the community, a lower lift-drag ratio and more noise at cutback, about 5 EPNdB. These data show that advanced takeoff procedures and systems have the potential to achieve community noise levels below FAR 36 and can provide flexibility to trade sideline and community noise levels to suit individual airport requirements.

CONCLUDING REMARKS

The NASA Supersonic Cruise Aircraft Research (SCAR) program has led to the identification of many technology advances which, if pursued, will make possible a much improved Supersonic Cruise Airliner. In particular, the integration of the technology advances in the areas of supersonic aerodynamics, variable-cycle engines, advanced takeoff procedures and systems, and co-annular noise effects through careful engine-airframe matching studies on a well validated baseline configuration has led to a configuration with greatly improved range, fuel consumption, economics and "off-design" characteristics.

REFERENCE

1. Jet Noise Prediction Aerospace Information Report No. 876A, Society of Automotive Engineers, July 10, 1965.

TABLE 1.- OBJECTIVES AND CONSTRAINTS

•	CRUISE SPEED	M = 2.2 TO 2.7
•	RANGE	
	NORTH ATLANTIC + INLAND CITIES	≈ 7041.4 km (3,800 nmi)
	PACIFIC	≈ 8338.5 km (4,500 nmi)
•	PAYLOAD	
	NO. OF PASSENGERS	180 TO 360
•	TAKEOFF FIELD LENGTH (SL, STD +10 ⁰ C)	3657.6 m (12,000 ft)
•	WING AREA	} AS SMALL AS POSSIBLE
•	ENGINE SIZE	
•	COMMUNITY NOISE	LOW
•	CLIMB PERFORMANCE	
	TRANSONIC THRUST MARGIN	0.30
	TIME TO CRUISE, HRS	0.75
•	CRUISE PERFORMANCE	
	<u>SUBSONIC RANGE FACTOR</u>	1.0
	SUPERSONIC RANGE FACTOR	

TABLE 2.- AIRPLANE CHARACTERISTICS

TOGW = 340,200 kg (750,000 lb)	} FIXED SIZE AND PAYLOAD, RANGE IS THE FIGURE OF MERIT
PAYLOAD = 273 PASSENGERS	
WING AREA = 715 m ² (7700 ft ²)	
OEW LESS ENG = 123,340 kg (271,920 lb)	
TOFL = 3,660 m (12,000 ft) (SL, STD + 10 ⁰ C)	
F _{NREQ.} = 198,000 N (44,500 lb) (SL, STD + 10 ⁰ C)	

TABLE 3.- ADVANCED TAKEOFF SYSTEMS AND PROCEDURES

SYSTEM/ PROCEDURE	APPLICATION	PURPOSE	ADVANTAGES
PROGRAMMED THROTTLES	AUTOMATIC THROTTLE MODULATION DURING TAKEOFF AND CLIMB	TAKING ADVANTAGE OF GROUND SHIELDING TO INCREASE THRUST DURING GROUND ROLL	HIGHER ALTITUDE AND/OR SPEED AT COMMUNITY, SHORTER FIELD LENGTH
PARTIAL FLAP RETRACTION	AUTOMATIC PARTIAL FLAP RETRACTION DURING INITIAL CLIMB	IMPROVE CLIMBOUT LIFT/DRAG RATIO	HIGHER ALTITUDE AND L/D AT COMMUNITY, LOWER CUTBACK POWER SETTING
CLIMB ACCELERATION	TRADE CLIMB CAPABILITY FOR ACCELERATION	IMPROVE L/D AT THE EXPENSE OF COMMUNITY ALTITUDE	HIGHER L/D AT COMMUNITY, LOWER CUTBACK POWER SETTING
AUTOMATIC PERFORMANCE RESERVE (APR)	AUTOMATIC INCREASE IN THRUST AFTER ENGINE FAILURE	ALLOWS LOWER 3 ENGINE CUTBACK POWER SETTINGS	LOWER CUTBACK POWER SETTING

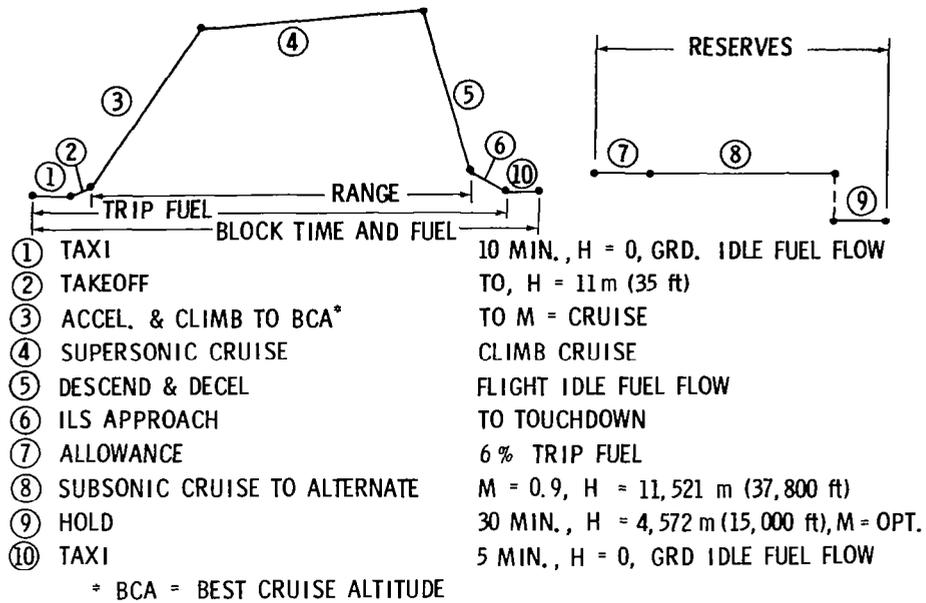


Figure 1.- Flight profile and reserves.

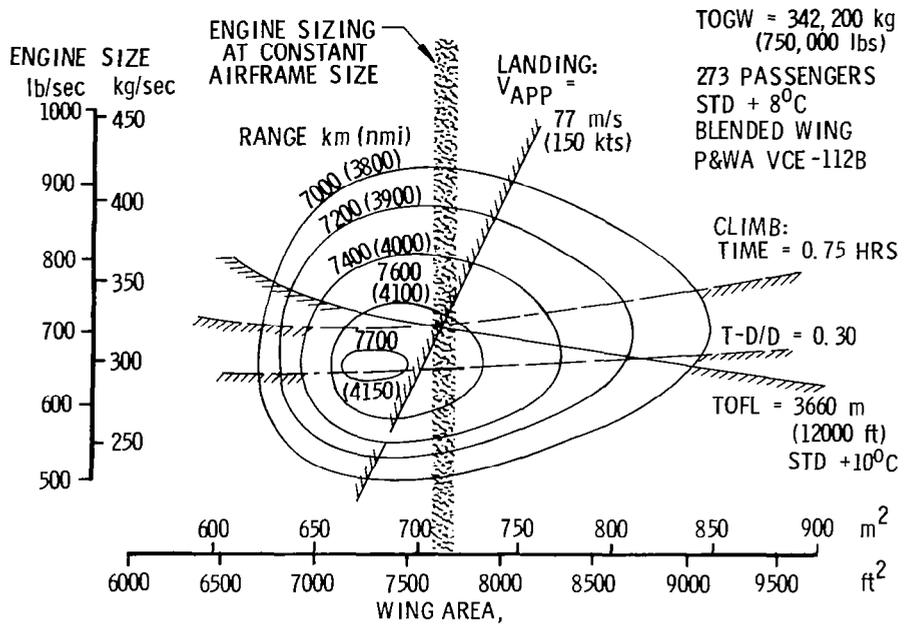


Figure 2.- Engine/airframe matching.

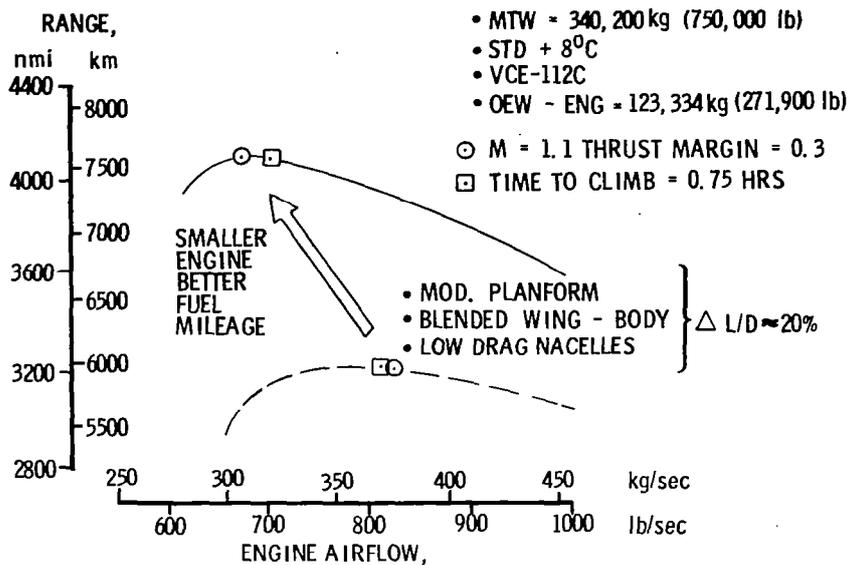


Figure 3.- Effect of supersonic aerodynamic improvements on range and climb characteristics.

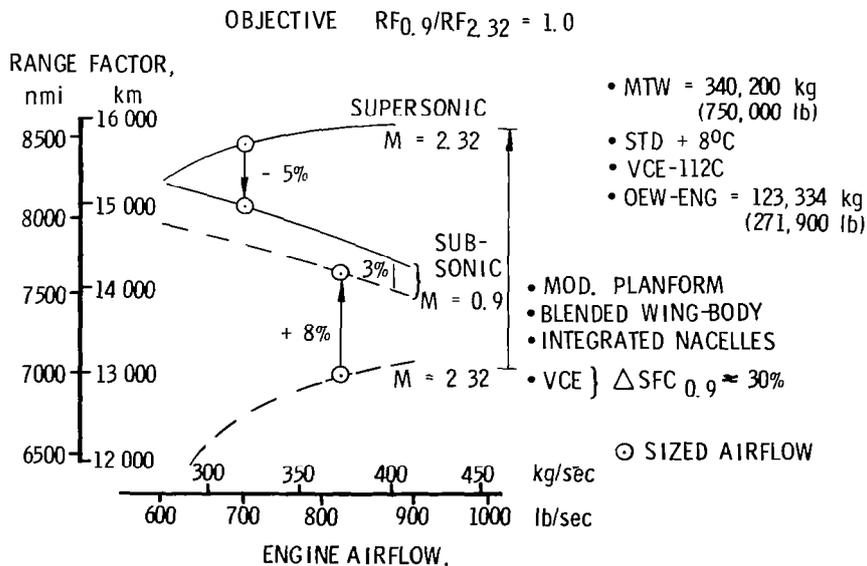


Figure 4.- Effect of supersonic aerodynamic improvements on cruise efficiency characteristics.

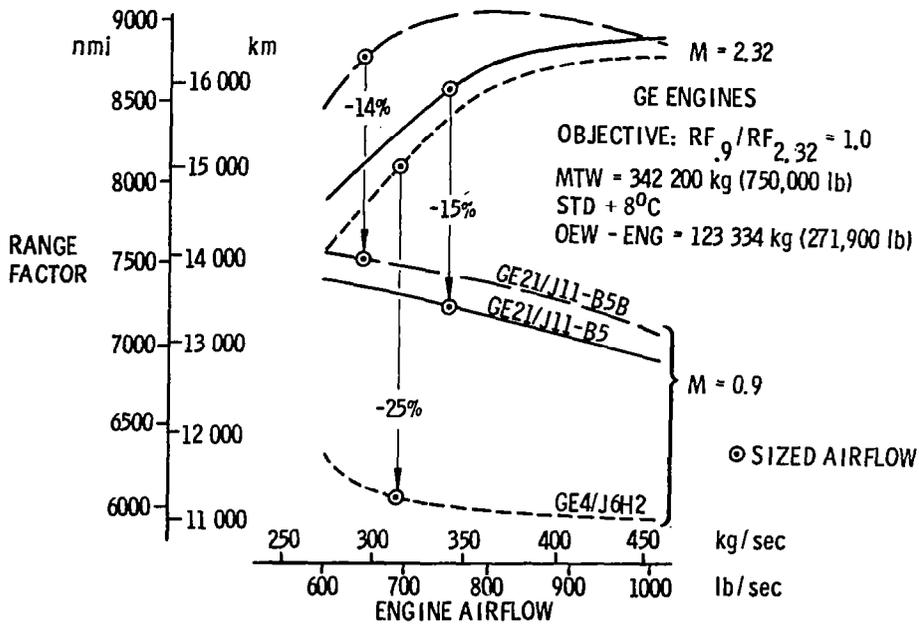


Figure 5.- Effect of engine cycle improvements on range and climb characteristics for GE engines.

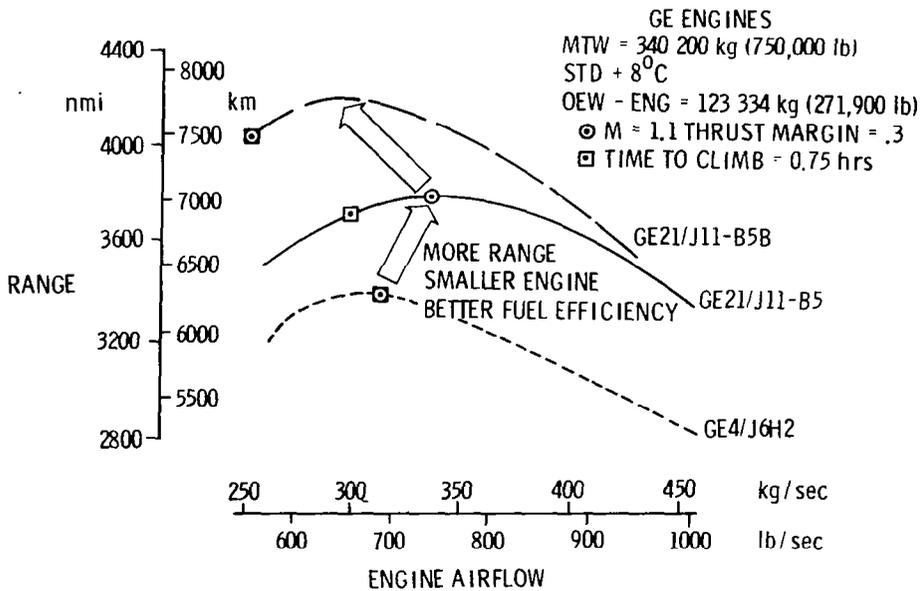


Figure 6.- Effect of engine cycle improvements on cruise efficiency characteristics for GE engines.

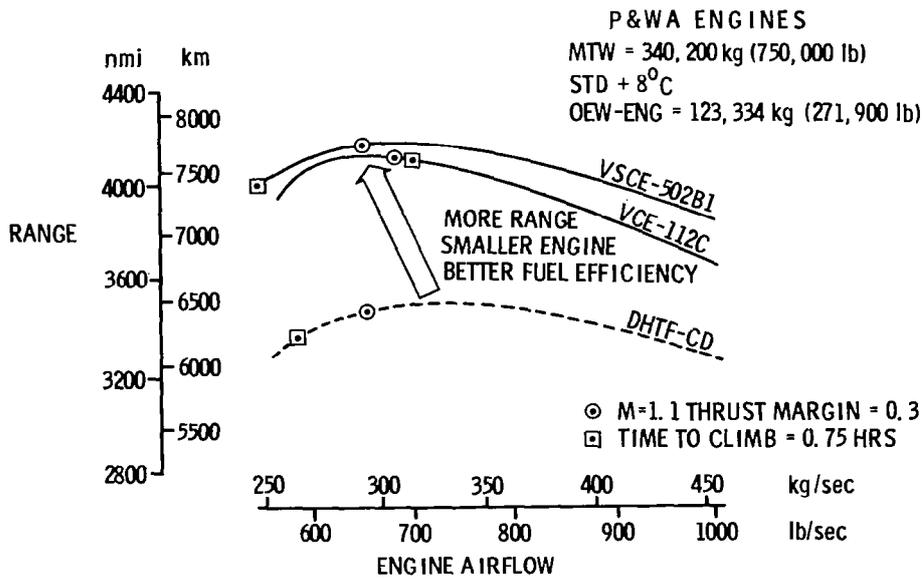


Figure 7.- Effect of engine cycle improvements on range and climb characteristics for P&WA engines.

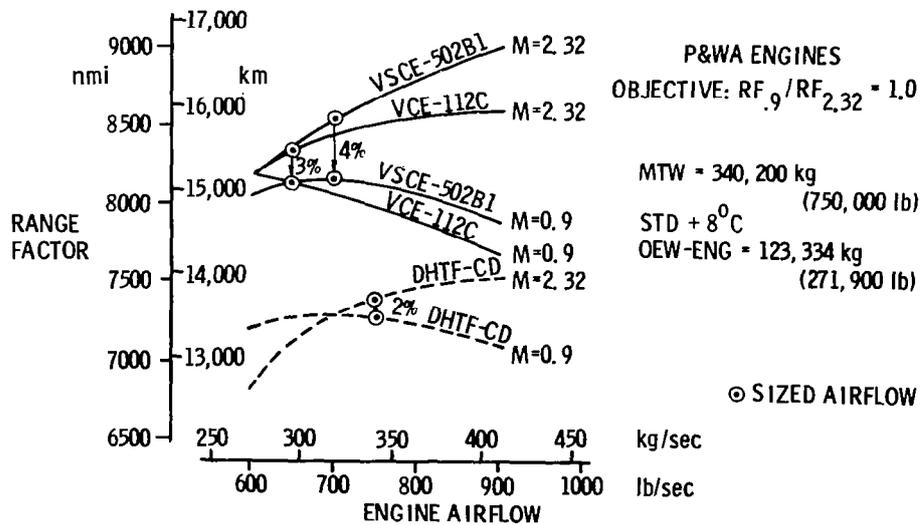


Figure 8.- Effect of engine cycle improvements on cruise efficiency characteristics for P&WA engines.

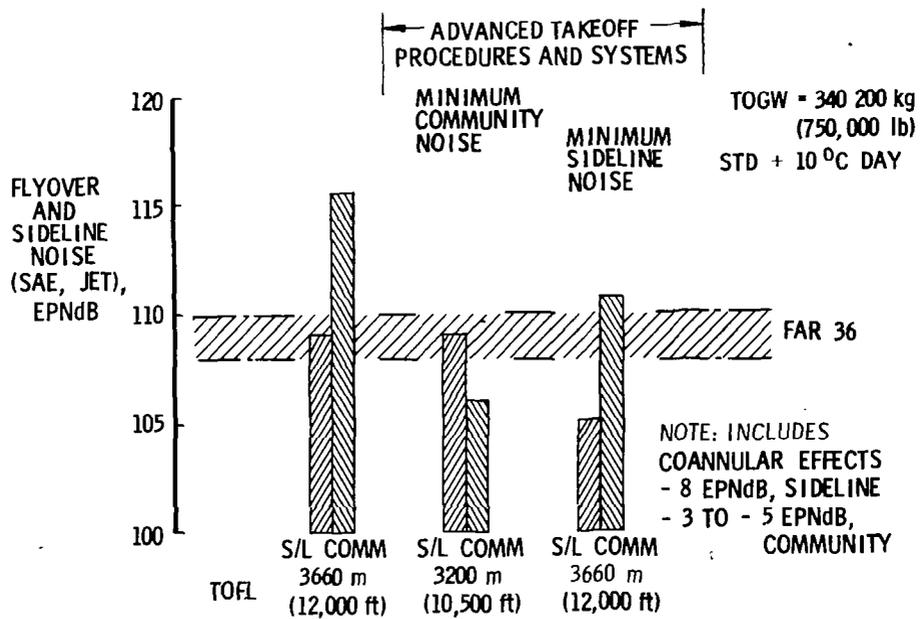


Figure 9.- Effect of advanced takeoff procedures and systems.